UDC 621.376.24:
621.396.62

1969
THE QUEEN'S AWARD
TO INDUSTRY

BBC

RESEARCH DEPARTMENT

REPORT

Single-sideband transmissions for m.f. broadcasting: compatibility experiments with conventional receivers

No. 1969/14

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

SINGLE-SIDEBAND TRANSMISSIONS FOR M.F. BROADCASTING: COMPATIBILITY EXPERIMENTS WITH CONVENTIONAL RECEIVERS

Research Department Report No. **1969/14**
UDC 621.376.24:
621.396.62

It uses SI units in accordance with B.S. document PD 5686.

Work covered by this report was undertaken by the BBC Research Department for the BBC and the ITA

D. Maurice
Head of Research Department

K. Hacking, B.Sc.

(RA-38)

Research Department Report No. 1969/14

SINGLE-SIDEBAND TRANSMISSIONS FOR M.F. BROADCASTING: COMPATIBILITY EXPERIMENTS WITH CONVENTIONAL RECEIVERS

(RA-38)

July 1969

Research Department Report No. **1969/14**
UDC 621.376.24:
621.396.62

SINGLE-SIDEBAND TRANSMISSIONS FOR M.F. BROADCASTING: COMPATIBILITY EXPERIMENTS WITH CONVENTIONAL RECEIVERS

SUMMARY

A brief investigation has been made into the distortion resulting from the reception of single-sideband and vestigial-sideband signals by an ordinary receiver with an envelope detector. Suitable modulators have been constructed and used to compare systems with different transmission characteristics. Listening tests have been performed to assess the degree of compatibility of a single-sideband-plus-carrier system. Of particular interest is the variation in the subjective effects of the system distortions with respect to both the type of programme transmitted and the relative strength of the carrier.

1. INTRODUCTION

Any move towards some form of single-sideband transmission for radio broadcasting in the m.f./l.f. bands, however attractive the ultimate benefits may seem, brings with it the immediate problem of compatability with enormous numbers of existing domestic receivers. The compatible single-sideband system (c.s.s.b.), as proposed by Kahn[1,2] and others,[3] has been studied in an earlier report.[4] The c.s.s.b. system is capable of a reasonable degree of compatability with existing receivers and it confines most of the transmitted r.f. signal power to a bandwidth equal to that of the audio signal. Another well-known alternative is simply to transmit a strong carrier plus one sideband, such as would be obtained, for example, by removing either the upper or lower sideband in a conventional double-sideband (d.s.b.) transmission. The envelope of the r.f. signal, to which the conventional d.s.b. broadcast receiver responds, is inherently distorted in this process but the severity of the distortion and hence the degree of compatibility depends on the strength of the carrier relative to the transmitted sideband.

This report presents the results of several subjective tests relating to the compatibility of a single-sideband-plus-carrier system (s.s.b.) with existing d.s.b. receivers. It is by no means an exhaustive study, but rather a pilot investigation to ascertain the possible reaction of critical and non-critical listeners to the non-linear distortion of music and speech resulting from this kind of transmission when received with an envelope-detecting receiver. No comment will be made here about the potential advantages and disadvantages of using a s.s.b. system with special receivers that would eliminate the distortion.

In order to establish a background against which the subjective results can be more easily appreciated, the types and relative magnitudes of the distortion components which may arise will be outlined, including measurements on the particular receivers used in the subjective tests.

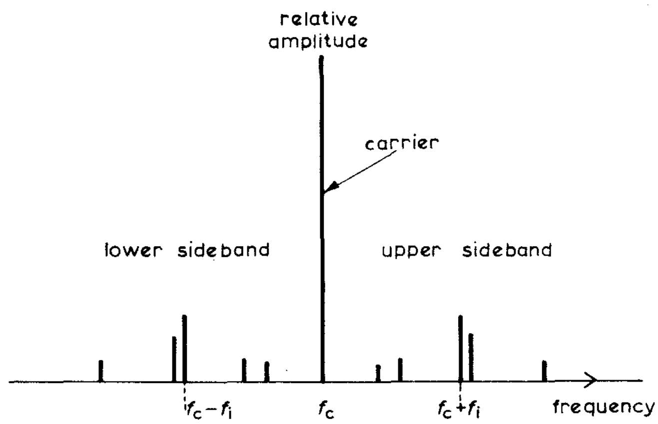

Fig. 1 - Amplitude spectrum of transmitted signal in a double sideband a.m. system: multitone modulation

2. NON-LINEAR DISTORTION

2.1. Theoretical Analysis

Fig. 1 shows the amplitude spectrum of a transmitted signal obtained when a r.f. carrier is amplitude modulated with a multitone audio signal. The spectrum comprises discrete components at frequencies which are symmetrically disposed with respect to the carrier frequency. In a conventional double-sideband transmission each of the modulating tones gives rise to a pair of spectral components of equal magnitude: one in the upper sideband at a frequency $f_c + f_i$ and one in the lower sideband at a frequency $f_c - f_i$, where f_c and f_i are the frequencies of the carrier and modulating tone respectively. In a single-sideband transmission one of the pair of components is either partly or completely suppressed.

An expression for a transmitted signal $E(t)$ representing a carrier (of unit amplitude) modulated by a number of

tones is

$$E(t) = \left[1 + \sum_{i=1}^{n} (a_i + b_i) \cos\omega_i t\right] \cos\omega_c t$$

$$+ \left[\sum_{i=1}^{n} (a_i - b_i) \sin\omega_i t\right] \sin\omega_c t \qquad (1)$$

where,

$\omega_c/2\pi$ = carrier frequency

$\omega_i/2\pi$ = frequencies of the modulating audio tones ($i = 1, 2, \ldots n$); $\omega_c \gg \omega_i$

n = number of tones

a_i, b_i = amplitudes of the lower and upper sideband components, respectively, corresponding to the i th tone.

For simplicity, it is assumed that the initial phases of the modulating tones and the carrier are all zero and that these phase relationships remain undistorted: this is implicit in Equation (1).

If $E(t)$ is the signal arriving at the input to a perfect envelope-detector, its low-frequency output $S(t)$ is given by

$$S^2(t) = \left\{1 + \left[\sum_{i=1}^{n} (a_i + b_i) \cos\omega_i t\right]\right\}^2 + \left[\sum_{i=1}^{n} (a_i - b_i) \sin\omega_i t\right]^2 \qquad (2)$$

It is seen from Equation (2) that if $a_i = b_i$ for all i, as in the double-sideband case, then

$$S(t) = \left|1 + \sum_{i=1}^{n} (a_i + b_i) \cos\omega_i t\right|$$

which is the original modulating signal undistorted, apart from a d.c. component, provided that

$$\left[\sum_{i=1}^{n} (a_i + b_i)\right] \leqslant 1.$$

In all other cases the output of the envelope-detector will be a harmonically distorted version of the original modulating signal.

The extent of the envelope distortion in a single-sideband system is best illustrated by the waveshape obtained for a single modulating tone, as shown in Fig. 2 for a 100% modulated carrier ($a_1 + b_1 = 1$). The output of a perfect envelope-detector for a d.s.b. transmission is shown in Fig. 2(a) while that for a s.s.b. transmission is shown in Fig. 2(b): the latter is seen to be a train of half sine-waves. A Fourier analysis of the latter particular waveform shows that it consists of a fundamental sinusoidal component plus many harmonic components whose amplitudes decrease with frequency. Thus if the fundamental frequency of the modulating tone is 400 Hz, say, we can expect all the harmonics up to the 10th to fall within a 4 kHz audio band, taken as the nominal pass band for an a.m. receiver. On the other hand if the fundamental frequency were 2·5 kHz even the second harmonic would fall outside the nominal pass band and the tone at the final audio output would be almost undistorted, although of reduced amplitude.

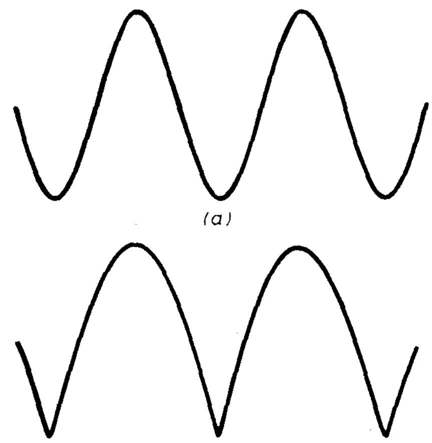

Fig. 2 - Single-tone waveforms at output of perfect envelope detector

(a) d.s.b. transmission (showing undistorted signal)

(b) s.s.b. transmission: 100% modulation depth

A single-tone analysis of the distortion to be expected in a s.s.b. system is, however, misleading because it masks the significance of the intermodulation distortion products which may arise with a multitone signal. A double-tone analysis is more revealing and the following section gives the results of a Fourier analysis[5] of Equation (2) for n = 2. Also, for comparison with theory, the magnitudes of the most significant distortion products were measured with the actual receivers used in the compatibility tests.

2.2. Distortion Measurements

Using a distortion analyser,[6] the magnitudes of the distortion products at the output of two ordinary, domestic radio receivers were measured. The general arrangement is shown in Fig. 3. The test tone was either a single tone or a double tone (two tones of equal amplitude and constant, 121 Hz, frequency difference) of variable frequency in the audio range. A description of the modulators and their spectral transmission characteristics is given in Section 3. Suffice it to say here that any one of three transmission systems, d.s.b., s.s.b. and a vestigial-sideband system (v.s.b.) could be selected by means of a switch. Also, with each system, there was provision for varying the amplitude of the attendant carrier and thus the modulation depth; the carrier frequency was constant at a nominal 1 MHz. The v.s.b. system can be regarded as a system in which there is a gradual transition from a double-sideband condition to a single-sideband one with increasing modulation frequency. The results below labelled 'v.s.b.' refer to a transition which takes place over the modulation frequency range 0 to 1·5 kHz (see Section 3). It is clear from Fig. 3 that the distortion measurements include any distortion of the enve-

lope due to imperfection of the modulators, although this is believed to be small compared with the s.s.b. system distortions.

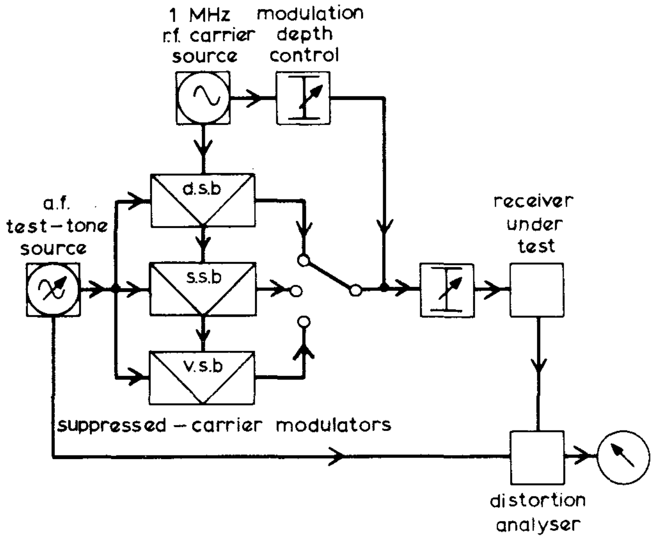

Fig. 3 - Arrangement for measuring distortion components

One of the receivers was a mains-operated valve receiver, while the other was a modern a.m./f.m. transistor portable. Both receivers would be classed as 'good quality' sets. The distortion was measured either at the detector output or at the output of the audio-frequency amplifier; for the transistor set this was at the 'tape' and 'personal' listening sockets respectively, but for the valve receiver, across the volume control and loudspeaker coil respectively.

A selection of measured results for the two receivers, together with theoretical calculations of the expected behaviour with a perfect envelope detector, are shown in Figs. 4 to 7.

In Fig. 4(*a*) the amplitude of the second harmonic relative to that of the fundamental (single-tone input at 500 Hz) is shown as a function of the modulation depth. The plot points are measured values at the detector output of the valve receiver, while the full-line curves are theoretical results for a perfect detector. Fig. 4(*b*) shows the variation with modulation depth of the $(f_2 - f_1)$ intermodulation product obtained with a double-tone modulating signal; the actual tone frequencies were f_1 = 500 Hz and f_2 = 621 Hz. The measured values, as in Fig, 4(*a*), refer to the valve receiver at the detector output.

Figs. 5(*a*) and 5(*b*) show measurements of the $(f_2 - f_1)$ intermodulation product taken at the audio-amplifier output, for each receiver. Fig. 5(*a*) refers to the valve receiver and Fig. 5(*b*) to the transistor receiver.

Figs. 6(*a*) and 6(*b*) show the measured relative magnitudes of the $(f_2 - f_1)$ intermodulation products for each system as a function of the fundamental frequency (f_1), from 300 Hz up to the edge of the receiver passband; the maximum modulation depth was kept fixed at 71%, and the distortion was measured at the audio-amplifier output of each receiver. Fig. 6(*a*) refers to the valve receiver and Fig. 6(*b*) to the transistor receiver.

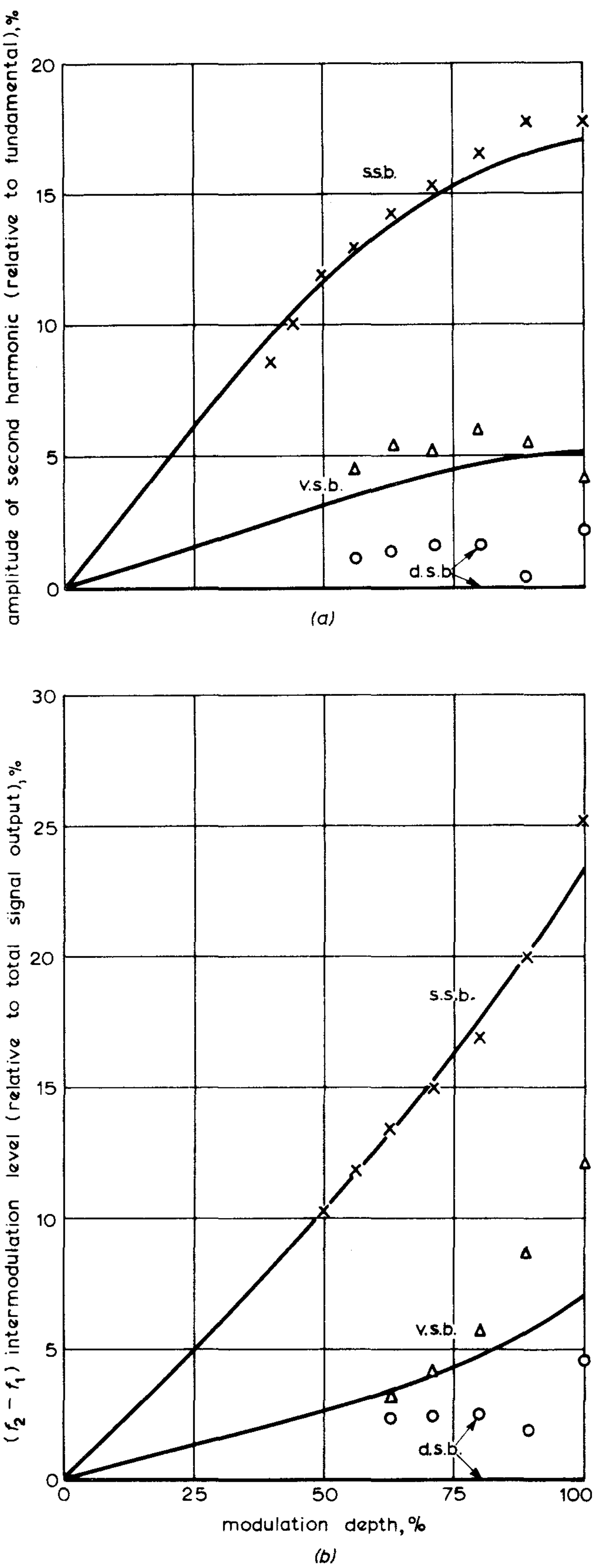

Fig. 4 - Relative distortion levels for the three systems

(*a*) 2nd harmonic (single-tone analysis)

(*b*) $(f_2 - f_1)$ intermodulation component (double-tone analysis)

O, X, Δ Measured values at detector output of valve receiver

——— Theoretical (perfect detector)

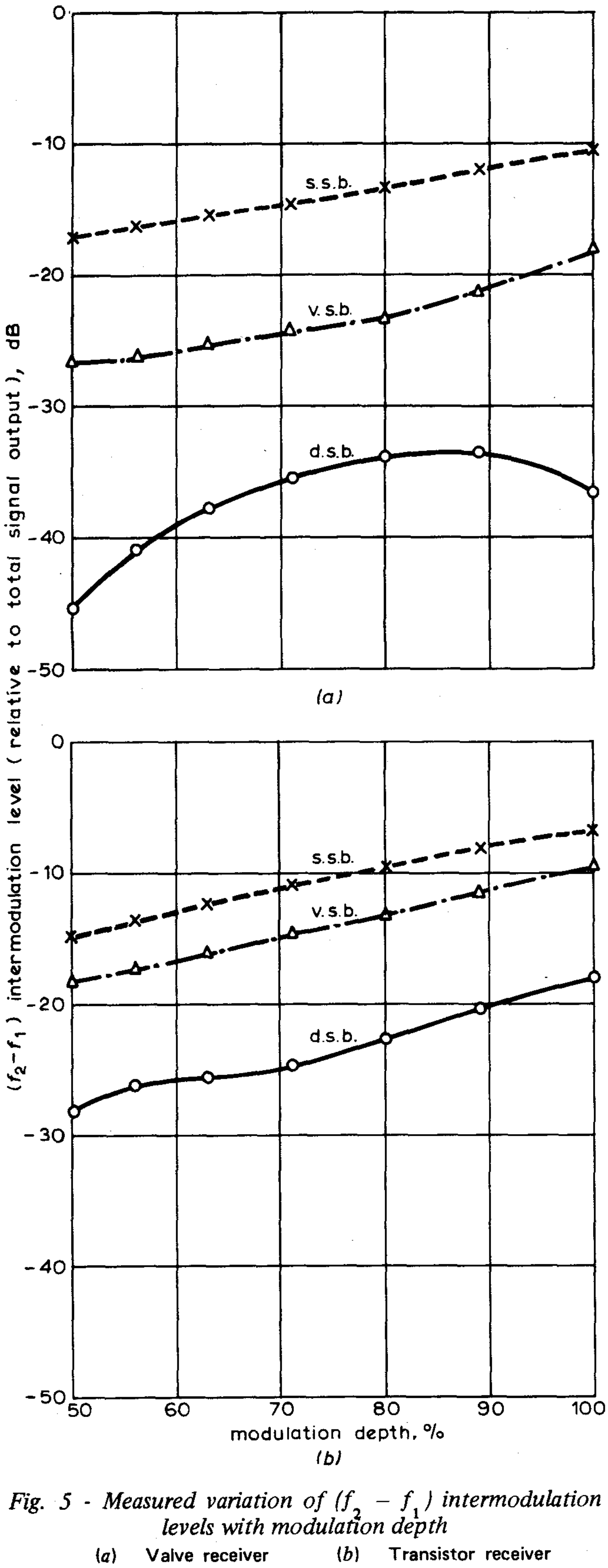

Fig. 5 - Measured variation of $(f_2 - f_1)$ intermodulation levels with modulation depth

(*a*) Valve receiver (*b*) Transistor receiver

(Measurements at audio-amplifier output. Double-tone test signal f_2 = 621 Hz, f_1 = 500 Hz)

o——o double sideband, x– – –x single sideband, Δ—·—Δ vestigial sideband

The intermodulation levels shown in Figs. 5 and 6 are the ratios (in decibels) of the time-averaged modulus of the $(f_2 - f_1)$ component to that of the total output signal. In Fig. 6, however, where the levels are plotted as a function of modulation frequency, the reference level is the total signal output at 300 Hz; also, the variation of the total signal output over the receiver passband is shown.

Fig. 7 is included to show the calculated relative levels of other, possibly less significant, intermodulation and harmonic components which are expected at the output of a perfect envelope detector with a s.s.b. system transmitting a double-tone audio signal. Here the amplitudes of the various distortion components are shown relative to the amplitude of the fundamental (f_1) and are plotted as a function of maximum modulation depth. The range of modulation depth has been extended to include the situation where overmodulation occurs. The magnitudes of the corresponding distortion products expected with a d.s.b. system when overmodulation occurs are also shown (full lines in Fig. 7).

2.3. Remarks on the Objective Results

The good agreement between the measurements on the valve receiver and the expected behaviour of a perfect detector, which is apparent from Figs. 4(*a*) and 4(*b*) for modulation depths less than 90%, indicates that this receiver is representative of a class of domestic receivers having a good standard of detector performance with regard to the fidelity of response to the r.f. envelope. Furthermore, there appears to be only a small increase in the measured distortion levels due to the a.f. amplifier stages.

It may be seen from Fig. 4(*a*), that the curve showing the second harmonic level in the s.s.b. system tends to flatten as the modulation depth approaches 100%. Consequently, a dramatic improvement in the distortion of a reasonably pure tone cannot be expected by limiting the maximum modulation depth of the system to 60% or 70%. However, if we look at the double-tone analysis, which indicates that for a s.s.b. system the difference-frequency intermodulation product is the most significant, at least numerically, it appears (Fig. 4(*b*)) that the distortion level increases more rapidly as the modulation depth increases. Thus the possibility of achieving a substantial improvement in compatibility by lowering the maximum modulation depth now seems more hopeful.

The effect of a gradual transition from double-sideband at very low modulation frequencies to single-sideband at intermediate frequencies, as in a v.s.b. system, is seen in Fig. 6, where distortion level is measured as a function of modulation frequency. Up to about 1 kHz, there is a substantial improvement in the distortion level with the v.s.b. system, which should alleviate the distortion problem for that kind of programme material (speech for example) whose spectral energy is largely concentrated at low audio frequencies. Although Fig. 6 shows results for the $(f_2 - f_1)$ intermodulation distortion product, there will be a corresponding improvement with the v.s.b. system in the levels of all the other distortion products arising from low frequencies. It should be noted, also, that above 1 kHz the dis-

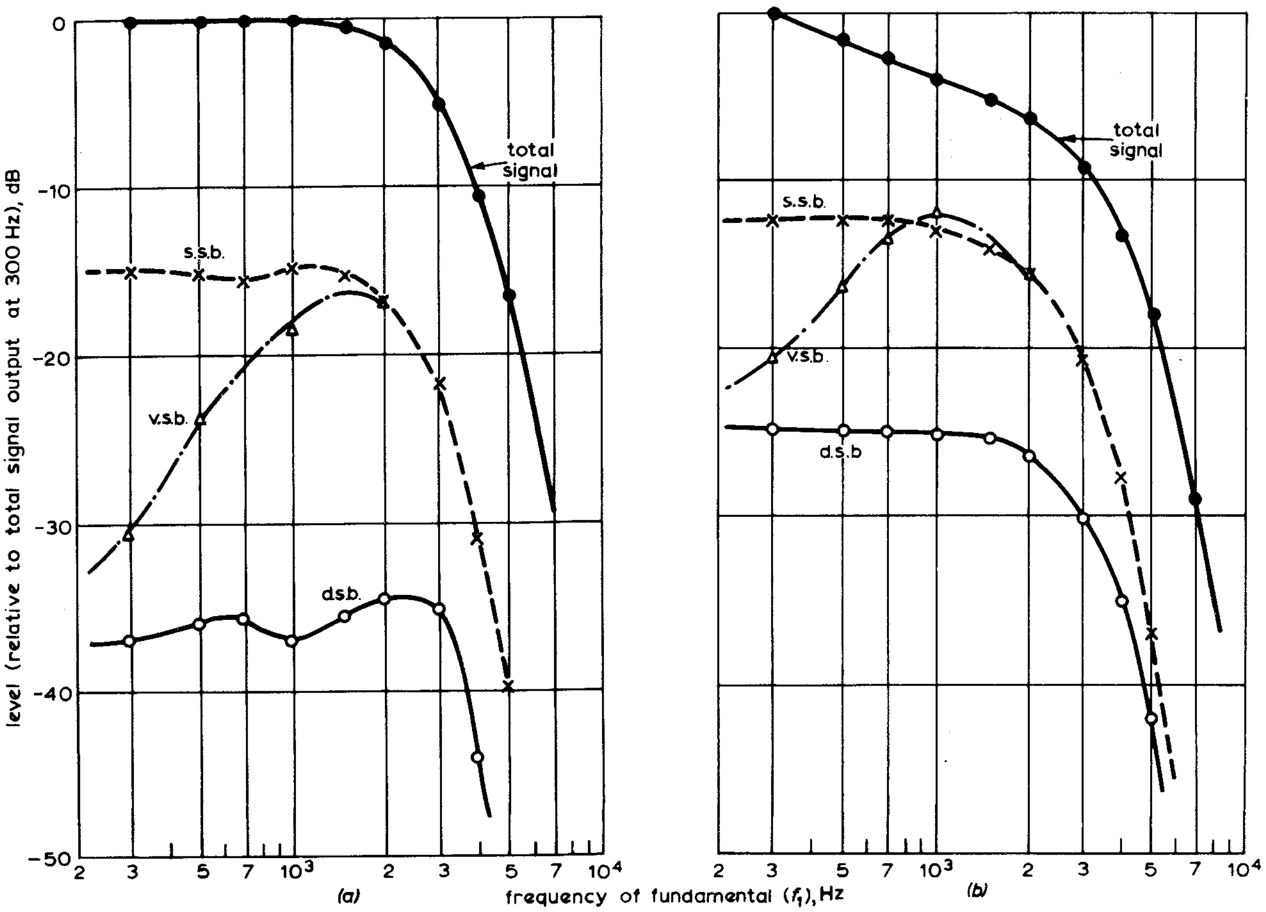

Fig. 6 - Measured variation of $(f_2 - f_1)$ intermodulation level and total signal level with frequency of fundamental (f_1)

(*a*) Valve receiver (*b*) Transistor receiver

double sideband, single sideband, vestigial sideband: $(f_2 - f_1)$ intermodulation component

total signal output (double sideband)

tortion levels of the v.s.b. and s s.b. systems are approximately the same, so that no significant improvement is expected with this particular v.s.b. system for programme material with strong spectral components above about 1 kHz.

The changes in the distortion levels of the various components with overmodulation, indicated in Fig. 7 for the double-tone situation, is interesting. It will be seen that as modulation increases with the s.s.b. system the difference-frequency components, including the strong $(f_2 - f_1)$ component, tend to continue increasing. The other products, however, tend to have maximum values near 100% modulation. The rapid increase in distortion level with overmodulation for the d.s.b. system should be noted. At 140% modulation depth, the levels of the second-order distortion terms for the d.s.b. system are approximately the same as for the s.s.b. system at 50% modulation, although this does not necessarily imply that the subjective effects are comparable.

The overall distortion levels using the transistor receiver are seen to be somewhat higher than with the valve receiver (Fig. 5), especially for d.s.b. and v.s.b. transmissions at high modulation depths. This is due partly to

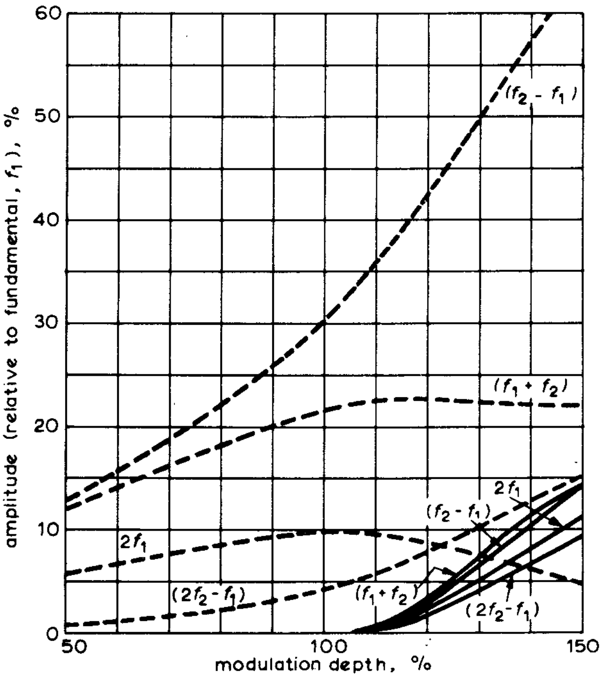

Fig. 7 - Double-tone analysis: calculated relative amplitudes of major distortion products (Perfect envelope detector)

Single sideband system . Double sideband system

an inferior detector performance above about 70% modulation and partly to distortion added in the a.f. stages of the receiver. How significant these receiver defects are in subjective intercomparison of the various systems is difficult to estimate, but the objective results for this particular transistor receiver indicate some masking of the system differences at high modulation depths.

3. THE MODULATORS

Low-power modulators were constructed so that by operating a single switch either a d.s.b., s.s.b. or v.s.b. signal was available with a pre-selected limit on the maximum modulation depth. The nominal transmission characteristics of the three systems are shown in Fig. 8, where it is assumed that the audio input is limited to frequencies between 60 Hz and 4·5 kHz approximately. In Fig. 8(*c*), the vestigial skirt of the v.s.b. amplitude characteristic has the form $\frac{1}{2}\left\{1 + [\sin \pi(f - f_c)/3]\right\}$, where f_c is the carrier frequency in kHz and $f_c - 1{\cdot}5 < f < f_c + 1{\cdot}5$. The phase characteristic over the vestige has the same anti-symmetrical property with respect to the carrier phase as in a normal d.s.b. system.

The form of the modulators is shown schematically in Fig. 9. The well-known phase shift method of obtaining a single-sideband signal was used, in which two double-sideband signals are produced using separate, balanced modulators so that when combined either the lower sidebands cancel and the upper sidebands reinforce or vice versa. One advantage of this arrangement is that a double-sideband signal of the same peak-to-peak excursion as the single-sideband signal is obtained by simply open-circuiting the input to one of the balanced modulators. A variable-amplitude carrier derived from the same r.f. generator was added, correctly phased, to the modulator output. The degree of suppression of the unwanted sideband[7] is largely governed by the accuracy of the wide-band, 90° audio phase-shift network. In theory, the phase-shift deviations from 90° over the effective audio band can be reduced to the required tolerance by increasing the number of phase-shift sections of the network. Three sections were used in each arm of the phase-shift network feeding the modulators described here: the overall suppression of the unwanted sideband obtained was better than −30 dB relative to the wanted sideband over an audio band of 120 Hz to 7 kHz. The ring of diodes in each of the modulators were driven hard by an external r.f. signal generator at the required carrier frequency (1 MHz). The diodes rings were balanced for good carrier suppression (about 50 dB).

The v.s.b. system was achieved by modifying the low-frequency part of the s.s.b. modulator, as indicated in Fig. 9. The a.f. input signal is switched to feed a low pass/high pass crossover filter. The low-frequency output reached the balanced modulators via a centre-tapped delay network arrangement, bypassing the normal audio phase-shift network through which the high-frequency components of the signal are passed. The delay network arrangement produces two output signals which are always in phase-quadrature but the amplitude of the spectral components of one of the signals is a function of their frequency. The amplitude

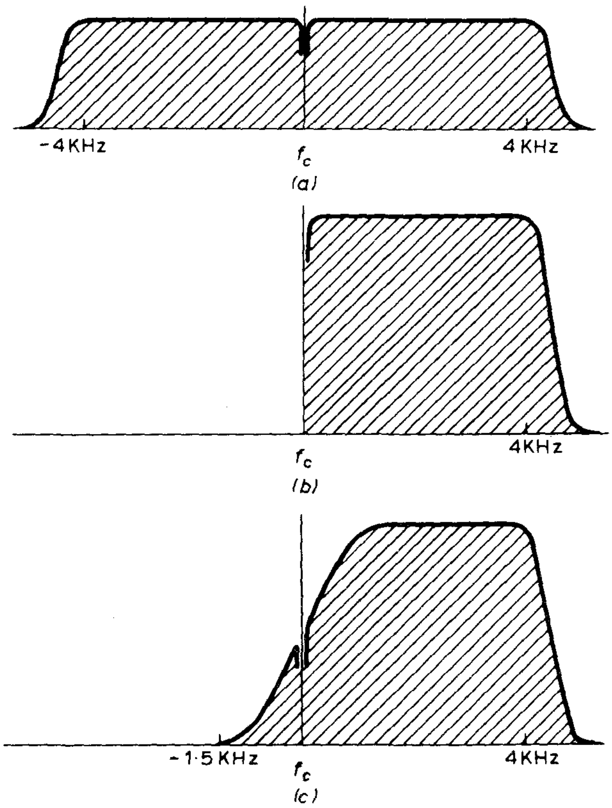

Fig. 8 - Nominal transmission – bandwidth characteristics
(*a*) double sideband (*b*) single sideband (*c*) vestigial sideband

varies from zero at frequencies n/τ to a maximum at frequencies $(n + \frac{1}{2})/\tau$, where τ is the total delay of the network and n = 0, 1, 2, 3.... Clearly, at very low frequencies the amplitude is small and there is very little input to one of the balanced modulators, hence the final output is double-sideband. However, for spectral components near the first maximum frequency $\frac{1}{2}\tau$, the amplitudes at the output of the delay network are arranged to be equal, resulting in a single-sideband output from the modulators. If the cross-over point of the low-pass/high-pass filter is arranged to coincide with the frequency $\frac{1}{2}\tau$, then the transmission characteristic will remain substantially single-sideband for the higher-frequency components. In the test described below the crossover frequency was selected to be approximately 1·5 kHz (τ = 330 μs).

4. ARRANGEMENTS FOR SUBJECTIVE TESTS

4.1. Scope of the Tests

The main purpose of the subjective tests was to assess listener reaction to the non-linear distortion effects on speech and music resulting from signal-sideband transmissions when received on ordinary domestic m.f. receivers. Of particular interest was the degree of subjective improvement which can be expected by limiting the maximum modulation depth of the transmitted carrier.

The transmissions were simulated in the laboratory by direct feed to the receiver from appropriate low-level modu-

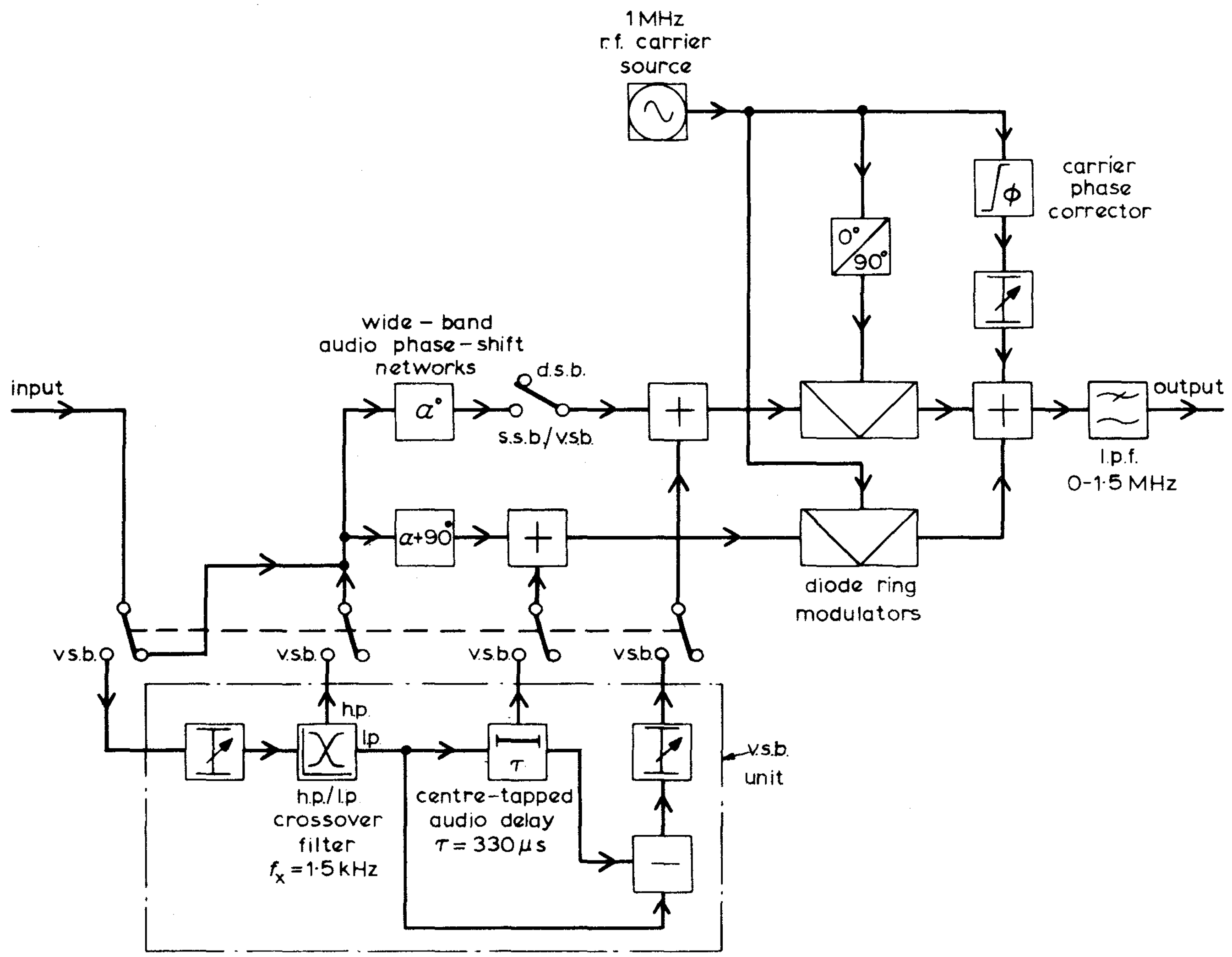

Fig. 9 - Arrangement for generating d.s.b., s.s.b. and v.s.b. signals

lators. Thus the received signal corresponded to that which would be obtained under almost perfect propagation conditions, i.e. devoid of distortions due to fading and interference from other sources. No attempt was made to assess the s.s.b. distortions under adverse conditions of reception.

The subjective tests took the form of preference judgements, on a better-or-worse scale, between the two systems under investigation either of which could be selected at will by the listener, as described in Section 4.3. The test programmes comprised a selection of short instrumental and choral passages as well as male and female speech, each of the passages being consecutively repeated at least four times to permit confirmation of initial reactions. A similar test programme consisting entirely of 'pop' music compiled from current gramophone records was also used for one test. Except for the latter test programme, audio compression of the signal was used prior to modulation and, for most tests, the audio bandwidth was restricted to 4·5 kHz.

One valve receiver and two transistor portable receivers were used in the tests. Most of the system comparisons, however, were carried out using the valve receiver, since objective distortion measurements showed this receiver to behave as a good envelope detector up to about 90% modulation. The receivers were tuned by the operator so that the transmitted carrier was in the centre of the r.f./i.f. pass band of the receiver; hence the overall frequency response was similar for both d.s.b. and s.s.b. systems.

About twelve listeners, all technical personnel, took part in one or more of a series of tests: most of the listeners taking part could be described as 'fairly critical' listeners.

4.2. General Arrangement

The complete layout of the equipment used in the tests is shown in Fig. 10. The test programme originated from a tape recording. The signal was first band-limited by a 4·5 kHz low-pass filter and then compressed, using a BBC type AM6/3A limiter operating in the 'compress' mode and set to introduce 10 dB of audio compression. After modulation the r.f. signal was filtered to remove any carrier harmonics generated by the modulators and then fed via an attenuator and matching pad to the aerial socket of the receiver.

The operator had a master switch to select the two systems to be compared, while the listener carrying out the

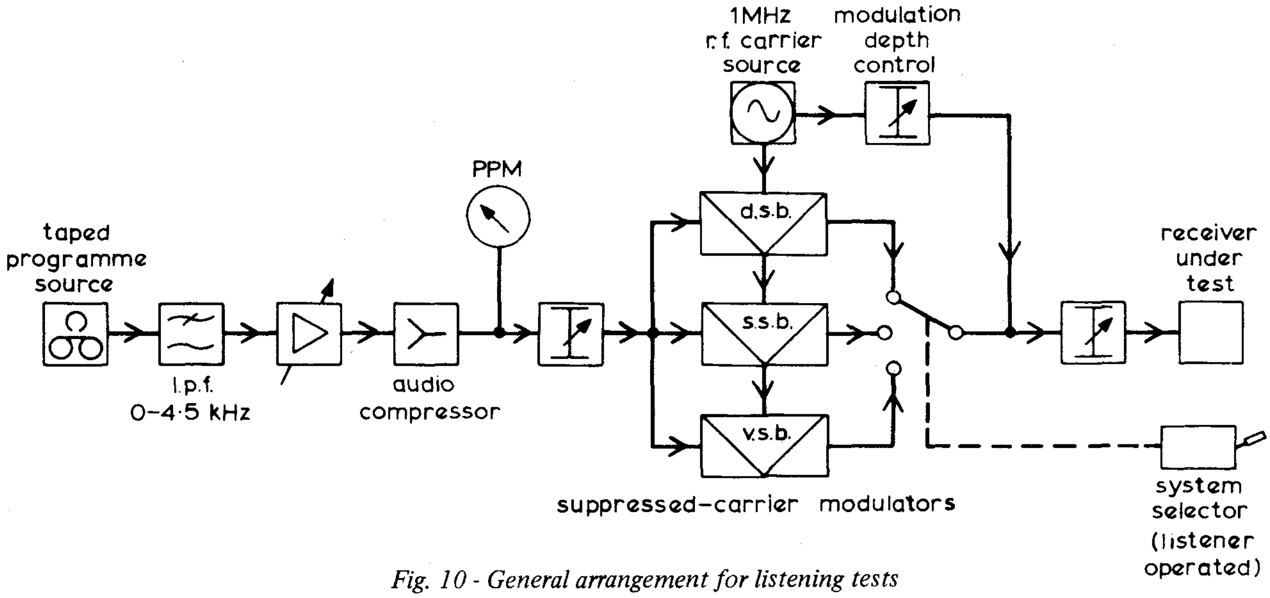

Fig. 10 - General arrangement for listening tests

subjective comparison was provided with a switch to change sequentially from one system to the other. A lamp indicator, placed close to the receiver, served to remind the listener which of the two switch positions he was currently using. The operator was able to limit the maximum modulation depth of the system by adjusting a calibrated attenuator.*

A double-beam oscilloscope was used to monitor the r.f. input and audio outputs of the receiver.

4.3. Test Procedure

After setting up the equipment and tuning the receiver with the aid of a variable-frequency oscillator as a modulating source, the listener was given a sample of test programme to adjust himself to the environment and the subjective task. According to a predetermined, irregular, sequence the maximum modulation depth of the transmission was changed for each of the eight distinct passages of programme which the listener was asked to judge. Calling the transmission systems being compared A and B respectively, the listener was asked to compare the quality of sound reproduction of system B with that of system A and score according to the following scale:

Much worse
worse
slightly worse
about the same
slightly better
better
much better.

* Occasionally, sharp peaks of modulation exceeding the nominal limit set by the operator were found to occur with some of the test passages. This was due to the finite attack-time of the audio compressor and/or the action of the modulator phase-shift networks. It is believed that their effect on the results of the subjective tests carried out was not significant.

The listener could switch between systems A and B as often as he felt necessary. Also, the operator was able to change the system which the listener had been asked to use as the reference.

A score was obtained for each of the eight passages (each passage was repeated at least four times) and by using eight listeners per test, with a different sequence of modulation depths for each, quality comparisons over a range of modulation depths from 45% to 90% were made. This procedure was repeated either with different systems for comparison or with a different receiver, although the same listeners did not always take part in every test.

5. RESULTS OF SUBJECTIVE TESTS FOR COMPATIBILITY

5.1. Effect of Programme Material

The type of sound material comprising the test programme was as follows:

Passage No.	Description
1	Xylophone (solo)
2	Eastern music (percussion)
3	Ladies choir
4	Dance band (ball-room type)
5	Male speech (news reading)
6	Female speech (news reading)
7	Piccolos
8	Piano (solo concert piece)

A second test programme consisting entirely of excerpts from popular records was also available. Audio compression was omitted when using this programme.

It became clear, from the results of the initial tests, that listener sensitivity to the distortions associated with the single-sideband transmissions was markedly affected by

the type of programme material. For example, Fig. 11 shows the scores obtained, averaged for all listeners with both valve and transistor receivers, when comparing the s.s.b. system with the d.s.b. system. The full line is the average score for the three most-sensitive passages (Nos. 1, 7, 8) as a function of the maximum modulation depth, while the upper dashed line is the corresponding result for the three least-sensitive passages (Nos. 2, 4, 5). The intermediate curve in Fig. 11 refers to the passages of intermediate sensitivity (Nos. 3 and 6), which were female singing and speech respectively.

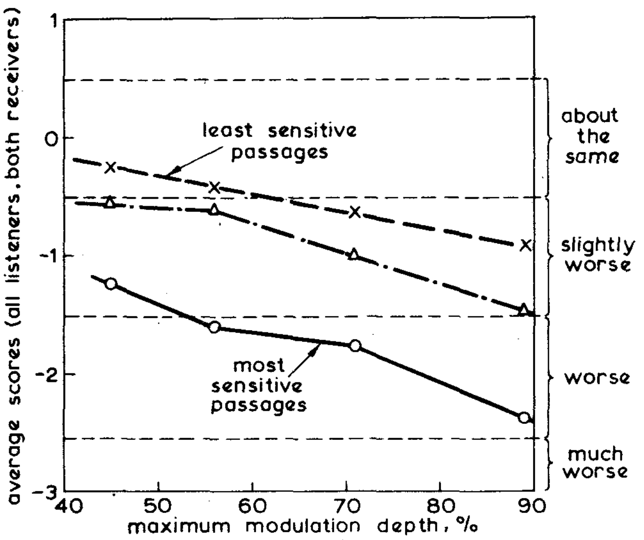

Fig. 11 - S.S.B./D.S.B. comparison: effect of programme material

5.2. Effect of Modulation Depth

Fig. 12 shows the overall scores obtained with the s.s.b./d.s.b. comparison as a function of maximum modulation depth when averaged over all listeners, all test passages (including the second 'pop' test-tape) and both receivers. It will be seen from both Figs. 11 and 12 that there is only a moderate improvement in the s.s.b. subjective distortion effects as the maximum modulation depth is reduced. The average rate of subjective improvement was found to be such that halving the maximum modulation depth from 90% to 45%, gave an improvement of approximately one subjective grade.

5.3. The V.S.B. System

A subjective comparison was made of the v.s.b. system with both the d.s.b. and the s.s.b. systems, using the same group of listeners and the valve receiver. The results of both experiments are shown in Fig. 13 where, in addition, the scores obtained for a s.s.b. versus d.s.b. comparison with the same observers, are included. It will be seen that a general improvement in quality was found with v.s.b. as compared with the s.s.b. system. It was particularly noticeable that the quality of speech was substantially improved with the v.s.b. system. However, a more detailed analysis showed little, if any improvement for the most-sensitive types of material at high modulation depths.

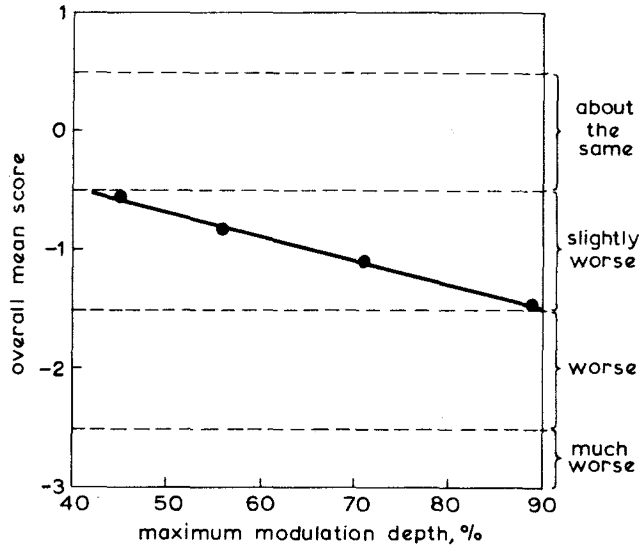

Fig. 12 - S.S.B./D.S.B. comparison: variation of overall mean score with modulation depth

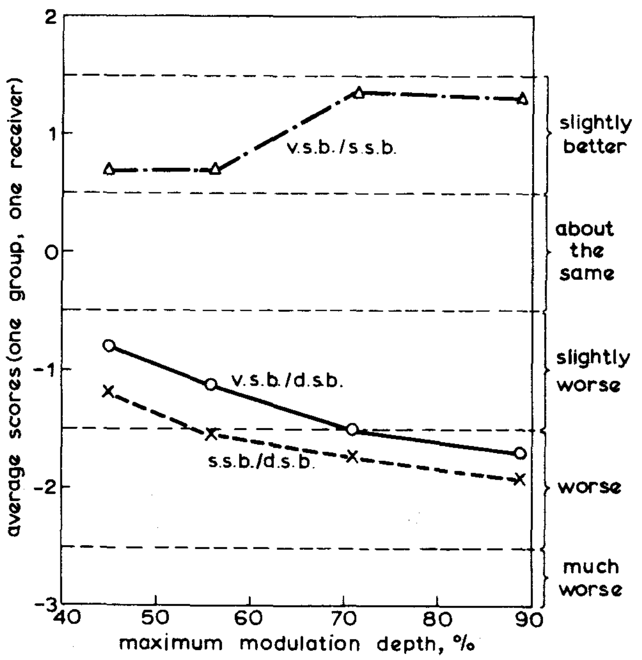

Fig. 13 - V.S.B. system comparisons: average scores for one group of listeners using the valve receiver

5.4. Receiver Differences

As expected from the objective measurements, there was little difference in the listener reaction to the system distortions reproduced on the two types of receiver below about 70% modulation depth. Above 70% modulation depth, however, the system distortions were found to be more obvious on the valve receiver. Fig. 14 shows the average results for all observers (as in Fig. 11): the full lines refer to the valve receiver and the dashed lines to the transistor receiver. It will be noted that at 90% modulation depth there is an apparent improvement in the subjective distortion effects with the transistor receiver, compared with that at 70%, for the least-sensitive material. This is explained by the modification of the s.s.b. distortion and the impairment of the d.s.b. performance due to the poor fidelity of the detector and a.f. amplifier stages in the transistor receiver at high modulation depths (see Section 2.3).

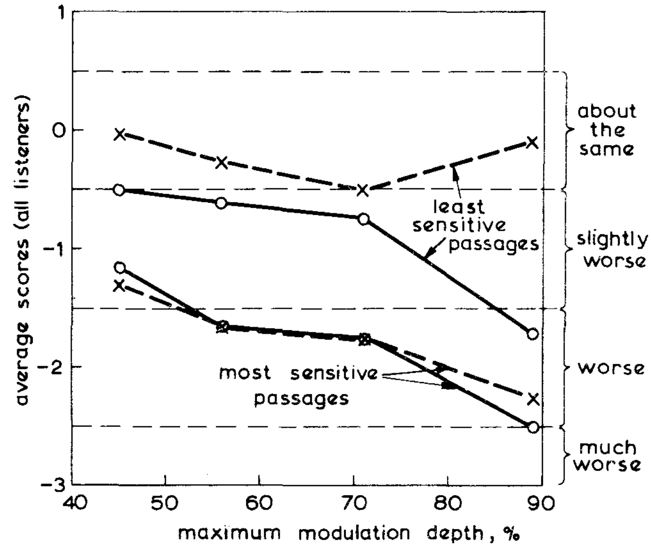

Fig. 14 - S.S.B./D.S.B. comparison: effect of receiver
—o— valve receiver —x— transistor receiver

6. DISCUSSION OF RESULTS

It is perhaps worth emphasizing several aspects of the conditions under which the tests were carried out before attempting to assess the results obtained.

In the first place the test programme signal was processed, prior to modulation, by filtering and compression. Thus the sound quality, even with a d.s.b. transmission, noise-free reception and a perfect receiver, could not be described as high-fidelity reproduction. Audio compression, varying from 6 dB to 12 dB, is at present applied in most BBC a.m. sound broadcasts, either at the transmitters or at the continuity studios. For this reason, compression was used in the tests reported here; additional tests without compression, however, indicated a significant reduction in the subjective effects of s.s.b. system distortions.

Secondly, the receiver tuning was carefully set so that the overall frequency response would be almost identical for both s.s.b. and d.s.b. transmissions. In practice, with s.s.b. transmissions, the receiver tuning might be offset (deliberately or otherwise) from the centred-carrier position and this would result in either an improved frequency response characteristic but worse non-linear distortion, or vice versa. The rate of exchange between overall frequency response and distortion will depend on the particular r.f./i.f. response characteristics of the reciever. Furthermore, adjacent-channel interference may easily influence the direction and extent of any deliberate tuning offset.

Lastly, in every individual judgement which the listener made he was asked to compare sound quality on one system with that on another, both systems having the *same* limit on the modulation depth. This procedure was used in order to obtain a clearer assessment of the s.s.b. system distortions; it avoided the possible masking effect of variations with modulation depth of additional non-linear distortion contributed by the receiver. Thus no direct subjective comparison was made between say, s.s.b. at 50% modulation depth and d.s.b. at 90%. If such a test had been made with the valve receiver, however, it is expected that the results as a function of s.s.b. modulation depth would not differ greatly from those presented in Section 5, because objective measurements showed that the additional distortion due to this receiver was relatively small. On the other hand, the same argument cannot be applied quite so confidently to the transistor receiver and the compatibility results for this receiver may not allow an accurate prediction to be made of the outcome of a direct comparison of s.s.b. at low modulation depths with d.s.b. at high modulation depths.

Notwithstanding these limitations on the scope of the tests, the results show a definite listener-reaction to the non-linear distortion effects on the s.s.b. system. In fact, only occasionally was there a quality judgement which indicated a definite preference for the s.s.b. system rather than the d.s.b. system, even with maximum modulation depths limited to 50%. Listeners are most sensitive to the type of 'splashing' distortion which occurs when the signal has a succession of strong spectral components at intermediate audio frequencies (1 to 3 kHz, say), e.g. a running piano scale. Strong intermodulation products are then produced which can sound most unpleasant, especially the lower-frequency components which occupy the otherwise vacant audio spectrum. Unfortunately, with this kind of programme material, the improvement obtained by limiting the maximum modulation depth is not dramatic, and the results indicate that a limit of 50% on the maximum modulation depth would be required to ensure a relative quality rating 'slightly worse'. For a large proportion of programme material, however, the quality would be rated only marginally worse than with d.s.b. transmissions, especially if the maximum modulation depth is limited to 70% or less.

The above general comments apply, also, to the v.s.b. system which was tested. If the extent of the vestigial slope of the transmission characteristic is effectively −1 kHz to +1 kHz, with respect to the carrier frequency, then the results indicate an overall improvement over s.s.b. of about one-third of a subjective grade. As expected, the improve-

ment is greatest (about 0·5 of a grade) for programme material, such as compressed speech, with energy concentrated at lower audio frequencies and transmitted at high average modulation depths. In terms of the difference in maximum modulation depth for equal subjective rating, the v.s.b. system shows an improvement over s.s.b. of between 15% and 20%. The total r.f. channel bandwidth for the v.s.b. signal was, however, approximately 6 kHz i.e. 30% greater than was used for the s.s.b. signal.

On the other hand, a v.s.b. system is advantageous for compressed speech and voice transmissions. A v.s.b. system, having a vestigial characteristic extending over ±1·5 kHz with respect to the carrier frequency would be a compromise arrangement with reasonable compatibility. Such a system would, however, require 6 kHz total transmitted bandwidth for an audio-bandwidth of 4·5 kHz.

7. CONCLUSIONS

The degree of compatibility of single-sideband-plus-carrier transmissions, assuming ideal propagation conditions, has been investigated briefly using ordinary, domestic (a.m.) receivers. A theoretical analysis of simple waveforms shows that the magnitudes of the low-order distortion products occurring with the s.s.b. transmissions can be large. Not surprisingly therefore, there was an unambiguous judgement that the quality of sound reproduction is inferior to that obtained with a double-sideband transmission under the same conditions. It is believed that the perception of strong, intermodulation distortion products accounts for the more marked deterioration in quality which is found with certain kinds of programme material. Furthermore, on these particular occasions, limiting the maximum modulation depth to less than 50% was found necessary in order to reduce the average listener reaction to the 'slightly worse' category. For most other kinds of programme material (indeed, probably the bulk of sound broadcast material) limiting the maximum modulation depth to approximately 70% is expected to ensure only a slight deterioration in sound quality for a receiver with a detector having a faithful response to the r.f. envelope. Additional non-linear distortion due to a poor detecting stage, or amplifier stage, in the receiver would tend, if anything, to diminish the difference between s.s.b. and d.s.b.

At the expense of r.f. bandwidth, the maximum modulation depth can be increased for the same degree of compatibility by using a vestigial sideband system. Unfortunately, at high modulation depths, no significant improvement in quality was obtained with the v.s.b. system investigated for the most-sensitive kinds of programme material.

8. REFERENCES

1. KAHN, L.R. 1957. A compatible single-sideband system designed for use in the broadcast service. I.R.E. Natn. Conc. Rec., 1957, **5**, 7, pp. 11 – 15.

2. KAHN, L.R. 1961. Compatible single-sideband. *Proc. Inst. Radio Engrs.*, 1961, **49**, 10, pp. 1503 – 1527.

3. VAN KESSEL, T.J., STUMPERS, F.L.H.M. *and* UYEN, J.M.A. 1962. A method for obtaining compatible single-sideband modulation. EBU Rev., 1962, **71A**, pp. 12 – 14.

4. Compatible single-sideband modulation: experimental investigation of the performance with conventional a.m. receivers. BBC Research Department Report No. G.100, Serial No. 1966/15.

5. Harmonic analysis of distortion in amplitude modulation systems with asymmetrical sidebands. BBC Research Department Report in preparation.

6. HARWOOD, H.D. 1963. Apparatus for measurements of non-linear distortion as a continuous function of frequency. BBC Monograph No. 49, July 1963.

7. GOURIET, G.G. *and* NEWELL, G.F. 1960. A quadrature network for generating vestigial-sideband signals. *Proc. Instn elect. Engrs.*, 1960, **107B**, 33, pp. 253 – 260.

SMW

Printed by BBC Research Department, Kingswood Warren, Tadworth, Surrey